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Patents ADP number *(if you know it)*

814337 2001

If the applicant is a corporate body, give the country/state of its incorporation

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4. Title of the invention

Apparatus for Dispensing a Sample in Electrospray Mass Spectrometers

5. Name of your agent *(if you have one)*

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Apparatus for Dispensing a Sample in Electrospray Mass Spectrometers

Background to the Invention

In mass spectrometry (MS), one of the intrinsic features of efficient electrospray or nanoelectrospray processes is the necessity to add volatile buffer and/or solvent to the sample in order to enable efficient evaporation in a controlled buffering environment. This requirement is sometimes incompatible with pre-spray activities that need to be performed for analytical, separation and/or purification purposes or that are required due to the specific properties of these volatile elements of the spray.

Mixing sheath liquid and sample after a separation

Different strategies have been presented to overcome this problem, which often consist in adding a pressurised flux conventionally called sheath liquid (often methanol, acetonitrile + acetic or formic acid) at the spraying orifice in order to mix the solution to be sprayed with this sheath liquid. In other systems, a sheath gas (i.e. a pressurised flux of gas like e.g. argon) is used to favour the evaporation of the sample solvent. These configurations, standard for electrospray ionisation (ESI), are compatible with systems that work with imposed and relatively high flow-rates of both the sheath liquid/gas and the solution to be sprayed (normally, larger than 5 microL/min).

In other cases, a liquid junction is introduced thanks to a T-cell at the end of the electrospray capillary in order to add about 50 % of sheath liquid as make-up flow so as to obtain a good spray. Again, these systems are efficient when the flow rates are large enough and well-controlled, but they often create quite large dead volumes which induce sample dilution and hence affect the sensitivity as well as the resolution of the detection.

In a nanoelectrospray, i.e. when the flow-rate is smaller than 5 microL/min, a liquid junction can also be used, but it is very difficult to control it efficiently because the pressure applied to the sheath liquid to mix with the solution to be sprayed often destabilises the flow in the main sample capillary. In case of separation, this may deeply reduce the resolution of the separated peaks. Finally, when the system is used for electrophoresis, the pressure applied on the sheath liquid can counter the electroosmotic flow and make the plug profile to be distorted which decreases the resolution of the separation.

In microanalytical devices, the possiblity to fabricate different channels and to interconnect them on the same chip enables to create liquid junctions with a minimum of dead volume, which reduces the sensitivity and resolution losses. Nevertheless, the main difficulty in electrospray and nanospray sampling with sheath liquids is to control the flow-rate of the sheath liquid and that of the sample solution. These flow-rates of course need to be in the same order of magnitude, so as to enable good and stable spray generation while maintaining a sufficiently high proportion of sample for the detection.

In order to control these flow-rates, some authors have derivatised the surface of a side arm to enable electroosmotic flow in the right direction in both channels, (Ramsey et al., Analytical Chemistry, 1997, vol. 69, p.1174). Other groups have integrated a liquid junction in the chip that is connected to a sheath liquid syringe through a capillary (Smith et al.). The microfluidic control in these systems is yet quite difficult and necessitates to fill the different arms of the chip without bubbles before starting the spray with real samples.

Reactions in the nanoelectrospray

Other applications such as chemical or biological reactions in the nanoelectrospray have been demonstrated and are expecting to deliver more information on tiny amounts of samples, particularly in proteomics where some digestions could be performed directly in the spray (Przybyslki). For example, nanoelectrosprays with immobilised trypsine have been used to digest a peptide and spray it on-line into

the MS, thereby enabling to follow the reaction kinetics. One of the main drawbacks yet relies on the fact that the trypsine, which can work in organic solutions, needs a pH of 8.2 to operate, whereas the spray would be more efficient at a pH of 3. As the volume and the flowrate are too small in the nanoelectrospray, it is difficult to introduce a liquid junction to add the sheath liquid. Therefore, these kinds of direct monitoring of reactions are very limited and are not yet considered as analytical tools.

In the present invention, we disclose a method and apparatus thereof to add the sheath liquid outside of the spray outlet, which enables to generate nanoelectroprays of pure aqueous solutions, even at high pH (pH 7 for example). The principle here is to add the sheath liquid, preferably without external pressure (syringe, pump or other), directly in the Taylor cone formed at the nanospray outlet, by removing any difficult mixing steps and preconditioning of the spray chip. With the present invention, separation (e.g. electrophoresis) or biological reactions (e.g. affinity, tagging, enzymatic reaction, polymerase chain reaction, etc.) can be performed in pure aqueous solution at any pH and can be conducted until the very end of the column. In addition, the mixing between the sample solution and the sheath liquid can take place in the Taylor cone only.

Summary of the Invention

From a first aspect, the present invention provides an apparatus for dispensing a sample for analysis by electrospray ionisation mass spectrometry, said apparatus comprising a substrate of electrically insulating material, the substrate comprising at least two covered microstructures (generally microchannels) both having an outlet at the edge of the substrate where the electrospray is generated, one microstructure containing the sample to be sprayed (hereinafter referred to as "sample microstructure") and at least a second microstructure (hereinafter referred to as "sheath liquid microstructure") containing a second solution,

preferably a sheath liquid, characterised in that the sample solution and the sheath liquid are directly mixed in the Taylor cone of the spray.

The apparatus may further comprise electrical means that allow to apply an electric field and to control it in both microstructures. The apparatus is notably characterised in that the flow-rates may be controlled in both the sheath liquid and in the sample microstructures, in that it may not be necessary to apply an external pressure to the sheath liquid and/or the sample solution for generating the spray (purely electrokinetic pumping) and in that pure aqueous sample solutions may be sprayed into the MS (thank to the mixing with the sheath liquid solution in the Taylor cone). The microstructure surface does not need to be derivatized in order to prevent fluid flow from the sample channel into the sheath liquid channel (or from the sheath liquid channel into the sample channel). In some applications however, portion(s) of the microstructure surface(s) may be fictionalized using chemical reaction(s) or immobilization procedures (like e.g. physisorption or covalent binding).

In this invention, the substrate is a solid support made of an electrically insulating material as for instance polymers, ceramics, silicon or glass.

In the present invention, there is no restriction about the micro-structure size, shape and/or position. The sample microstructure may have different shape and dimensions than the sheath liquid microstructure. Preferably, the microstructures are microchannels that yet have either width or height of less than 150 micrometers. Otherwise, the microstructures may advantageously form and/or be connected to a network of covered microstructures, so that the apparatus may then constitute and/or be coupled to a micro-total analysis system, which generally consists of a network of capillaries or microstructures used for instance for capillary electrophoresis, chromatography or affinity separation. In some applications, the microstructure may even be reduced to micro-holes created in the thickness of the polymer support or in the layer used to cover one or all microstructures. As well, arrays of apparatuses of this invention may be fabricated in the same polymer support and exposed to the MS. Furthermore, there is no

restriction about the technology used to create the microstructures: for instance, embossing, injection molding, casting, wet or chemical etching, physical etching like laser photoablation, plasma etching or UV-Liga, silicon technology or superposition of layers at least one comprising mechanically drilled grooves, hollows or holes may for instance be used to fabricate the microstructures. In some applications, the microstructures, the reservoirs and the polymer substrate may advantageously comprise electrodes and/or electrical contacts. The electrodes and electrical contacts may be directly integrated during the apparatus fabrication process, and the electrodes may then constitute a portion of one of the microstructure walls. Laser photoablation, plasma etching or superposition of layers comprising mechanically drilled grooves, holes or hollows and/or electrically conducting means would be specially well suited for such electrodes and/or electrical contact integration.

There is no limitation in the shape of the microstructure outlets. It has yet been noted that sharp angles may favor the spray generation and stability, but no theoretical explanation has been found for this phenomenon.

In one embodiment of the invention, the microstructures are formed in the same plan, so that the outlets of the sample microstructure and of the sheath liquid microstructure are adjacent. In another embodiment, the microstructure outlets are not in the same plane or even one over the other. In this case, the substrate may be a multilayer body, one layer comprising one of said at least two microstructures and another layer comprising a second of said at least two microstructures. In another option, one microstructure may be formed on one side of the polymer substrate, whereas the second microstructure is formed on the opposite side of the polymer substrate. In a further option, one microstructure may be formed in the cover used to seal the other microstructure (this can notably be the case of a micro-hole formed in the lamination layer used to seal the sample microstructure, said microhole being directly used to introduce the sheath liquid solution at or close to the outlet of the sample microstructure where the spray is then generated). For ease of manipulation, it may yet be advantageous that all

microstructures have access holes (or inlet reservoirs) on the same side of the polymer substrate.

In all configurations, it is advantageous that the distance between the outlet of the sample microstructure and that of the sheath liquid microstructure is smaller than 200 microns, so that the Taylor cone formed during the spray encompasses both outlets. This short distance allows efficient mixing of the solutions and prevents formation of liquid drops at the microstructure outlets, which facilitates the spray generation and favors the spray stability. In certain cases, the sample microstructure and the sheath liquid microstructure are connected at the edge of the substrate, thereby forming a unique outlet. In this case, the two microstructures are confounded only at the position of the Taylor cone, and the sheath liquid microstructure is thus different from a liquid junction.

In another embodiment, the apparatus has at least one dimension smaller than 500 micrometers, as in thin film microstructure devices. In this manner, only a small surface surrounds the microstructure outlets, thereby preventing drop formation and hence favoring the spray generation. The apparatus may also be formed in a multilayer substrate, in which each layer of said multilayer substrate may comprise one of at least two microstructures.

In a further embodiment, the outlet ends of the apparatus may exhibit a V-shape in the spraying direction or may be three-dimensionally etched in order to minimize the solid surface area around the outlets and/or to taper in the spraying direction.

In another embodiment, the covered microstructures are sealed by gluing, lamination or pressure application of a polymer foil. Such polymer foil is preferably a thin plastic layer which has to be resistant to the solvents used. In another embodiment, a portion of the sample microstructure may be in direct contact with a supplementary microstructure and/or comprise a solid support like beads or a membrane separating these two microstructures so as to perform diffusion-controlled assay prior to but on-line with MS sampling. This last

configuration may be advantageously used for physicochemical characterisation of compounds (lipophilicity, permeation tests or the like) or as purification or separation step. In permeation assays for instance, the membrane separating the two microstructures may contain a solution (generally, an organic phase supported in the membrane which separates two aqueous solutions).

In a preferred embodiment, the polymer substrate and/or the cover are formed in a hydrophobic material. In another embodiment, the surface of the microstructure(s) is hydrophilic so as to favor microfluidic control. For facilitating the spray generation, it may be advantageous to couple both characteristics of hydrophobic substrate material and hydrophilic microstructure surface, since the sample solution would easily flow within the microstructure while drop formation at the outlet will be minimized due to the hydrophobic nature of the substrate surrounding the spray outlet.

In another embodiment, the apparatus comprises conductive means, namely one or a plurality of integrated electrodes that are used to apply the voltage required for the spray generation, to electrokinetically pump the liquids within the sample and/or the sheath liquid microstructure(s), to induce a reaction either in the sample solution or in the sheath liquid, to perform electrochemical detection of a compound or any combination thereof. In a further embodiment, one electrode is integrated in the polymer support at a controlled position close to the microstructure outlet(s) and is in contact with the solutions placed in the microstructure(s). In another embodiment, the polymer support further integrates a second electrode placed at the microstructure inlet(s) or in a reservoir surrounding such inlet(s). In any of the above configurations, the conductive means may comprise a metallic layer, a conductive ink, a conductive polymer such as e.g. polypyrrole or polyaniline, a conductive gel, an ion permeable membrane like an ionode or any combination thereof. The voltage used to generate the spray as well as the spraying current density may thus be controlled by this electrically conductive means. In some applications, this conductive means may yet be an

external electrode in contact with one or the inlet reservoir(s) of the microstructure(s).

For certain applications, the sample should not be in direct contact with the electrically conductive means per se. In such a case, the conductive means may comprise an conductive electrolyte like an organic material, an aqueous gel or solution, a sol-gel or any material that physically isolate the electrode from the sample while maintaining electrical conductivity of the system.

In some applications, the sample microstructure and the sheath liquid microstructure may be put in electrical contact. In this manner, a high voltage may for instance be imposed along the sheath liquid microstructure in order to initiate the spray and to maintain it, whereas a second voltage may be superimposed in the sample channel. This superimposed voltage may induce a flow of sample solution. A power supply may be connected to each microstructure in order to generate the required applied voltage. The spray source of the mass spectrometer may be used to apply the voltage in one of the microstructures (generally in the sheath liquid microstructure). An independent power supply may then be used to apply the voltage in the second microstructure (generally the sample channel). In this manner, the MS entrance and the power supply are connected to the ground and the electric fields are applied in the two microstructures. In some applications, the sample microstructure may be electrically connected to the sheath liquid microstructure. A floating potential is then applied between the two microstructures to control the electric field in both microstructures.

In another embodiment of the invention, the sheath liquid microstructure contains a solution that is volatile enough to be used as sheath liquid. Methanol, acetonitrile or mixtures of methanol or acetonitrile and water are examples of such solutions that are also commonly used in electrospray ionization mass spectrometry. The solution contained in the sheath liquid microstructure may advantageously contain acid(s) or base(s) that favor(s) ionization of the sample to be dispensed into the MS. In another embodiment, the sample and/or sheath liquid solution(s) may also comprise a compound that will be ionized upon

generation of the spray and further dispensed into the MS. Such compounds may be advantageously used as internal standards and may notably serve as calibrant(s) for quantitative MS analyses.

The sample and sheath liquid solutions may be applied directly in the inlet reservoirs of the respective microstructures and sprayed into the MS, even without application of an external force (e.g. back pressure).

Generally, the apparatus is supported in a device facilitating the handling of the apparatus and/or allowing precise positioning of the spray tip (microstructure outlet) in front of the MS entrance. The supporting device may advantageously comprise liquid connection means (like e.g. capillary) to enable easy sample and/or sheath liquid introduction in the microstructures of the apparatus (and generally with minimized dead volumes), as well as electrical connections for application of the electric field(s). The dispensing of sample by electrospray ionization may also be automated and/or computer controlled , thereby enabling the control of the entire MS analyses (sample introduction, spray generation, flow-rates of sample and sheath liquid solutions in the microstructures, mixing of the two solution in the Taylor cone, sample ionisation, MS detection mode, etc.).

In some embodiment, the sample microstructure is connected to other separation or detection means like e.g. a chromatography column, an electrophoresis unit, a membrane, a desalting step, etc. In another embodiment, the sample microstructure may also comprise a separation means, like a solid phase (e.g. a membrane, beads and/or a section of the microstructure wall), a chromatography medium or a capillary electrophoresis system. For applications where the sample channel is coupled to and/or comprises a separation means like e.g. capillary electrophoresis, it may be advantageous to integrate a decoupler located between the separation means or the separation part of the sample microchannel and the sample outlet.

In a further embodiment, compounds may be coated, adsorbed or bounded on the microstructure surface. This may notably be use for physicochemical

characterization of compounds (as e.g. solubility assays), where the sample to characterize is coated on the walls of the sample microstructure. The solution in which the solubility has to be assessed is then introduced in the sample microstructure, and the sample dissolved in this solution after a given time may then be measured by mass spectrometry using the apparatus of this invention.

In another embodiment, the sample microstructure contains a biological material, as e.g. proteins, enzymes, antibodies, antigenes, sugars, oligonucleotides or cells, which may be immobilized or covalently bound to the microstructure surface or to a solid support (e.g a membrane, a gel, a sol-gel or beads), so that enzymatic, affinity, activity, immunological and/or cellular assays may be performed in the sample microstructure.

Many reactions that do not support solvents conventionally used in mass spectrometry (e.g. organic solvents like acetonitrile or methanol) may be performed in the apparatus of this invention since the sample may be a purely aqueous solution. Enzymatic reactions, affinity tests, solubility assays, enzymatic or chemical digestion, sample derivatization as well as electrochemically induced reactions (e.g. protonation, tagging using quinones or any other redox reactions) may thus be performed in the sample microstructure prior to dispensing into the mass spectrometer.

From a second aspect, the present invention provides a method of dispensing a sample into a mass spectrum from an apparatus as defined above. The method is characterized in that the electric field may be applied in both the sample and the sheath liquid microstructures and that the flow-rates of the solutions contained in these two microstructures may thus be controlled, thereby allowing to control the mixing of sample and sheath liquid solutions in the Taylor cone and hence their proportion in the spray. The method of this invention may advantageously be used for dispensing an aqueous sample solution into a mass spectrometer, even at high as well as at low flow rates, and even at high pH values.

The method of this invention may also comprise introducing a compound of known concentration in either or both of the sample and/or the sheath liquid solutions (internal standard(s) used for calibration) so as to enable quantitative MS detection of an analyte. In addition, the introduction of internal standards in the solutions may be used to measure the proportion of sample and sheath liquid solution sprayed and to assess the efficiency of the spray and/or of the mixing of the solutions in the Taylor cone.

The method may further comprise coupling the MS detection of a compound with purification or separation of the sample solution (e.g. by chromatography, capillary electrophoresis, affinity coupling, desalting, etc.) Similarly, the method may comprise immobilizing molecules of the sample reversibly on a solid support (e.g. a membrane or beads) and releasing said molecules from the solid support into the sample microstructure by spraying a buffer or by a gradient of different solvents. This solid support may also comprise an immobilized affinity agent(s) such as antibodies, antigenes, oligonucleotides, DNA strains and the like. The method may also comprise performing solubility assays, in which the sample microstructure may for instance be coated with a compound of interest before introduction and further spraying of a solution in which said compound dissolve.

In a third aspect, the present invention provides a method of fabricating an apparatus for dispensing a sample for subsequent analysis by electrospray mass spectrometry, comprising the step of taking a substrate of electrically insulating material, fabricating at least two covered microstructures, both having an outlet at the edge of the substrate so that the solutions to be sprayed from the microstructures through these outlets are mixed in the Taylor cone.

In one embodiment, the substrate may be a multilayer body, one layer comprising one of said at least two microstructures and another layer comprising a second of said at least two microstructures. The microstructures may be fabricated independently in the two layers. In this manner, the apparatus of the present invention may be fabricated by assembling two or more of the above layers (e.g. by gluing them together or by laminating them one over the other) in such a

manner that a multi-layer substrate is formed with at least two covered microstructures, both having an outlet at the edge of the substrate so that the solutions to be sprayed from the microstructures through these outlets are mixed in the Taylor cone.

In a further embodiment, the microstructure outlets at the edge of the substrate may be fabricated by cutting the substrate in its thickness, e.g. by mechanical means like a puncher.

Otherwise, the method of fabrication of the present apparatus may further comprise steps to integrate electrical means directly in the substrate, said substrate thus comprising at least one conductive portion.

When the substrate is a polymer, the covered microstructures may be formed by laser photoablation, UV-Liga, embossing, injection molding, solvent casting, light or thermal induced polymerization, silicon technology or superposition of layers at least one comprising mechanically drilled grooves, hollows or holes. The conductive portion of the substrate may also be formed by the deposition of an ink, conductive polymer, ion exchange material, metal deposition, sputtering or other. Alternatively, the microstructures and/or the conductive portion may be formed by plasma etching, photoablation or chemical etching. Conductive substrate portions formed in these ways are ideal for applying a high voltage in the microchannel in order to generate a stable spray for feeding a mass spectrometer.

The conductive substrate portion may in particular be formed by making a recess in the substrate and filling the recess with electrically conductive material.

An analytical instrument comprising an array of apparatuses, each according to the invention, can be used in a method of analyzing a plurality of samples, each apparatus being used in turn to collect a sample, and each sample can be dispensed from the respective apparatus, and analyzed by mass spectrometry.

Said samples may be collected from an analytical system, e.g. a chromatograph, an electrophoretic unit, a separation unit or an affinity system.

Description of the Invention

The invention is hereinafter described in more details by way of examples only, with reference to the accompanying figures, in which:

Figure 1 is an example of apparatus according to the present invention which is made in a substrate 100 and which comprises two covered microstructures, namely a sample microchannel 1 and a sheath liquid microchannel 2 that are connected to inlet reservoirs 3 and, respectively, 4 placed on the same side of the support 100 for fluid introduction. Figure 1 also illustrates that the microstructures have an outlet 6 formed at the edge of the support, at which the spray shall be generated upon voltage application;

Figure 2 shows the same example of apparatus as in Figure 1, in which the Taylor cone 5 formed upon potential application encompasses the outlets 6 of both the sample and sheath liquid microchannels, so that the sample solution mix with the sheath liquid solution directly in the Taylor cone;

Figure 3A shows an example of an array of apparatuses fabricated on the same support 100, said apparatuses comprising one sample microstructure 1, one sheath liquid microstructure 2 and one supplementary (but optional) microstructure 12 (all are microchannels in the present example) that are respectively connected to reservoirs 3, 4 and 13 and that have one outlet extremity 6 formed at the edge of the support where the Taylor cone 5 is created upon generation of the spray; this figure further illustrate that the support may be cut in a straight way or in a tip shape in order to decrease the solid surface area around the microstructure outlets and that the support may integrate electrical means like conducting pads 11 and/or electrodes 7, 8, 9 or 10 that are placed either in the microstructures or in contact with the microstructure inlets;

Figure 3B represents a variety of cross sections (along axis *a* of Figure 3A) of one of the apparatuses shown in Figure 3A and illustrates that the microstructure outlets may have various types of shapes and dispositions;

Figure 4 shows an example of device that can be used to support the apparatus of the present invention; in this example, the supporting device 20 comprises an electrical contact 21 connected to an electrical pad 11 integrated in the substrate 100 comprising the sample microstructure 1 and at least one sheath liquid microstructure (not shown); the supporting device 20 further comprises a fluid connexion means (here a capillary) which allows to introduce fluids at the inlet of the sample microstructure;

Figure 5 shows the evolution of the mass spectrum intensity as a function of the difference of applied voltage between the sample microstructure and the sheath liquid microstructure, ΔU, using an example of apparatus of the present invention in which the sample solution is an aqueous solution of 100 µM propanolol and caffein in 10 mM ammonium acetate at pH 5.5 and the sheath liquid solution is a solution of reserpine in methanol containing 1% acetic acid; Figure 5A shows the evolution of the mass spectrum at m/z= as a function of time; Figure 5B shows the evolution of ΔU as a function of time; Figure 5C shows an example of mass spectrum obtained upon a potential difference between the sample and the sheath liquid microstructures of 400 Volts; Figure 5D shows an example of mass spectrum obtained upon a potential difference between the sample and the sheath liquid microstructures of 0 Volt;

Figure 6 shows A) the evolution of the mass spectrum intensity of propanolol (i.e. at the mass-over-charge ratio of m/z = 259-261) and of reserpine (m/z = 608-610) as a function of time upon variation of the difference of applied voltage between the sample microstructure and the sheath liquid microstructure, ΔU; and B) the evolution of the ratio of the mass spectrum intensity of propanolol over that of reserpine as a function of ΔU, for the experimental data of Figure 6A; and

Figure 7 shows an example of apparatus of the present invention, in which the sample microstructures 1 is directly connected to a network of microchannels 30 and 31 comprising various connection reservoirs 32 and, respectively 33 and 34; the reservoirs 32 and 34 are connected to pumping means 36 and 37 (electrokinetic or mechanical pumping systems, symbolized here by syringe pumps), whereas reservoir 33 is connected to a capillary that allows sample introduction; such a configuration of apparatus may be advantageously used for connection to a separation system such a high-performance liquid chromatography column or a capillary electrophoresis unit; the sample may be continuously pushed into the inlet 33, whereas the pumping means allow to control the direction of the sample flow and hence the injection of the sample in the sample microstructure; as an example, the pumping means 37 may be used in pulling mode in order to aspirate the solution arriving from the capillary 35 at the inlet 33, while the pumping means 36 is used in a pushing mode in order to further force the fluid to flow from inlet 33 to reservoir 34 which is then used as a connection to the waste; by switching the pumping means 37 and 36 to pushing and, respectively, pulling, then the sample solution flows from inlet 33 towards reservoir 32; the sample solution may then be injected into the sample microstructure 1 by application of a voltage between reservoir 3 and the spray outlet of the sample channel; this configuration of apparatus allows very accurate injection of sample and, in some applications, the sample may be further separated within the sample microstructure prior to be sprayed.

The concept of the present invention is demonstrated by way of the following experimental data obtained with an apparatus similar to that schematically shown in Figure 1. The apparatus made of two plasma etched microchips made of a polyimide foil having a thickness of 75 µm, comprising one microchannel (~60mm x ~120 mm x ~1 cm) sealed by lamination of a 38 µm thick polyethylene/polyethylene terephthalate layer and one microelectrode (~52 µm diameter gold electrode) integrated at the bottom of the microchannel. The two polyimide chips were glued together and further mechanically cut in a tip shape, in such a manner that this multilayer system exhibits two microstructures both

comprising a microchannel having an outlet at the edge of the polyimide layers, thereby forming an apparatus where the outlets of the sample and sheath liquid microstructures were superposed and where the Taylor cone could be formed similarly to the configuration shown in Figure 2. With this apparatus, the thickness of the support separating the two microstructure outlets was less than 50 micrometers. It should also be noted here that the apparatus further comprised inlet reservoirs at the entrance of both the sample and the sheath liquid microstructures. A polystyrene well was further glued on the top of each reservoir so as to increase the volume of sample and sheath liquid solution to be placed in the apparatus. In addition, the integrated electrode was not used to apply the voltage in the present experiments. To generate the spray, the voltage can yet applied directly in the polystyrene reservoirs, for instance 2 kV being applied in the sheath liquid reservoir and 2 to 2.5 kV in the sample reservoir.

In order to use this apparatus to dispense an aqueous sample solution into an electrospray mass spectrometer (here a LCQ-Duo from Finnigan, USA), an example of method is described hereinafter:

1) place the apparatus in front of the MS entrance with the microstructure outlets directed toward the MS orifice (typically from few microns to few centimeters)

2) fill the sample microstructure 1 by capillary action for example with an aqueous sample solution (here 10 mM ammonium acetate at pH 5.5 with 100 µM propanolol and caffeine) by depositing a drop in the sample reservoir (typically a solution volume of few nanoliters to few microliters);

3) fill the sheath liquid microstructure 2 by capillary action with a sheath liquid solution (here methanol containing 0.1 or 1% acetic acid and 100 µM reserpine) by depositing a drop in the sheath liquid reservoir;

4) start the spray in the sheath liquid microchannel 2 by applying a voltage (here 2 kV) in the sheath liquid reservoir 4;

5) pump the sample solution in the sample microstructure 1 by applying a supplementary voltage (+ΔU = 100 to 500 V) between the sample and the sheath liquid reservoirs 3 and 4 in order to generate a flow of sample solution by electrokinetic pumping.

As a demonstration, Figure 5 shows the evolution of the mass spectrum intensity as a function of the difference of applied voltage between the sample microstructure and the sheath liquid microstructure, ΔU, using the above described example of apparatus and method. Figure 5A clearly shows that the total MS intensity varies with time, and follows the time variation of the supplementary voltage ΔU applied in the sample microstructure. When ΔU is large, the MS intensity is high, which corresponds to the increased ion concentration detected by the MS due to the large proportion of sample solution sprayed. When ΔU decreases, the MS intensity decreases since the proportion of sheath liquid solution increases.

This is also confirmed by the full spectra shown in Figure 5C and 5D that have been measured at ΔU values of 400 and 0 V, respectively. At ΔU = 400 V, the largest peak intesity is recorded at m/z = 260.4 (corresponding to propanolol), whereas the peak at m/z = 609.6 (corresponding to reserpine) is very low, which signifies that the proportion of sample solution sprayed is large. In contrast, at □U = 0 V, reserpine is detected with the highest intensity, whereas propanolol is detected in much lower intensity than at ΔU = 400 V, thereby confirming that the proportion of sample solution sprayed is much lower than at ΔU = 400 V. This is further exemplified in Figure 6A, which shows the time evolution of the mass spectrum measured for propanolol and reserpine upon variation of ΔU.

The ratio of the peak intensity measured for propanolol over that measured for reserpine may be reported as a function of ΔU. As exemplified in Figure 6B, this ratio drastically increases with ΔU, which is in agreement with an increased proportion of sample solution sprayed. Such a calibration curve may then be used to evaluate the flow rates in the sample and sheath liquid microstructures. As illustrated in Figures 5C and 5D, the ratio of the peak intensities for propanolol

and caffeine, which are both present in the sample solution, remain the same upon variation of ΔU. This also shows that the calibration curve of Figure 6B may further be used for the quantitative determination of a compound. In such a case, reserpine and e.g. caffeine may be used as internal reference for both the sheath liquid and the sample solution.

It must be stressed here that the supplementary voltage ΔU will only be applied in the channels if there is a liquid connection between the sample and the sheath liquid microstructures. In the present invention, this liquid "bridge" is the Taylor cone generated by the first voltage. In this manner, the apparatus of this invention is particularly efficient because the pumping in the sample microstructure (aqueous sample solution) is effective only after that the spray has been initiated (thereby minimizing undesired stop of the spray). In addition, the flows of sample and sheath liquid solutions in the Taylor cone may be easily varied by changing the value of the imposed supplementary voltage ΔU. By addition of a compound of known concentration in each solution, the proportion of the sheath liquid and sample solutions sprayed can be monitored by the intensity recorded by the mass spectrometer. This strategy also enables to perform quantitative MS analysis, with much more accuracy than conventional methods.

Claims

1) An apparatus for dispensing a sample for analysis by electrospray ionization mass spectrometry, said apparatus comprising a substrate of electrically insulating material, the substrate comprising at least two covered microstructures both having an outlet at the edge of the substrate where the electrospray is to be generated by application of a voltage and an inlet for fluid introduction, one microstructure containing the sample solution to be sprayed and at least a second microstructure containing a second solution, preferably a sheath liquid, characterized in that the sample solution and the sheath liquid are directly mixed in the Taylor cone of the spray.

2) An apparatus according to claim 1 wherein said substrate is a multilayer body, preferably of polymer material(s), in which at least two layers of said multilayer body comprise one of at least two microstructures.

3) An apparatus according to claim 1 or 2, having a thickness smaller than 500 µm.

4) An apparatus according to any preceding claim, which comprises electrically or ionically conductive means for applying a voltage to the sample and/or sheath liquid solution(s), said conductive means having a controlled size and location.

5) An apparatus according to claim 4, wherein said conductive means comprises one or a plurality of electrodes and/or one or a plurality of electrically conductive pads.

6) An apparatus according to claim 5, wherein said conductive means is(are) integrated in one wall of said microstructure(s) and/or is in contact with the solution(s) at the inlet(s) of said microstructure(s).

7) An apparatus according to any of claims 1 to 3, wherein the spray voltage is applied through external electrically or ionically conductive means arranged to be

in contact with the solutions to be sprayed, for instance by pouring said conductive means in the solutions to be sprayed at the inlets of said microstructures.

8) An apparatus according to any of claims 4 to 7, wherein said conductive means comprises an electrically conductive ink, or a metallic layer, or a conducting polymer such as e.g. polypyrrole or polyaniline, or a conductive gel, or an ion exchange polymer arranged to be in contact with the solutions to be sprayed.

9) An apparatus according to any preceding claim, wherein the distance between the outlet of the sample microstructure and that of the sheath liquid microstructure is smaller than 200 μm.

10) An apparatus according to claim 9, wherein the sample microstructure and the sheath liquid microstructure are connected at the edge of the substrate, thereby forming a unique outlet.

11) An apparatus according to any preceding claim wherein said microstructure outlets taper in the spraying direction.

12) An apparatus according to any preceding claim wherein the microstructure outlets are hydrophobic or are surrounded by a hydrophobic material.

13) An apparatus according to any preceding claim, wherein said microstructures have at least one dimension of less than about 150 μm.

14) An apparatus according to any preceding claim, wherein said sample microstructure and/or said sheath liquid microstructure communicate(s) with a network of microstructures.

15) An apparatus according to any preceding claim, wherein said sample microstructure has a hydrophilic surface.

16) An apparatus according to any preceding claim, wherein said covered microstructures are sealed by gluing, lamination or pressure application of a polymer foil.

17) An apparatus according to any preceding claim, wherein said sample solution is an aqueous solution.

18) An apparatus according to any preceding claim, wherein one of said sample microstructure contains a biological or a chemical material, such as e.g. proteins, enzymes, antibodies, antigenes, sugars, oligonucleotides, DNA, cells or an organic compound, which is filled in said microstructure or which is coated, immobilized or covalently bound to the microstructure surface or to a solid support (such as a membrane, a gel, a sol-gel, beads or the like), so as to perform a biological assay such as enzymatic, affinity, activity, immunological and/or cellular assays and/or to perform a chemical assay such as solubility, permeability or lipophilicity tests and/or to perform enzymatic or chemical digestion, sample derivatisation or electrochemically induced reactions such as protonation, tagging using quinones or any other redox reactions.

19) An apparatus according to any preceding claim, wherein said sample microstructure comprises a separation means, comprising at least one of a solid phase, a chromatography medium or a capillary electrophoresis system.

20) An apparatus according to claim 19, wherein said separation means comprises a solid phase selected from a membrane, beads and/or a section of the microstructure wall.

21) An apparatus according to any preceding claim, wherein said sample microstructure is connected to a separation means like e.g. a chromatography column, an electrophoresis unit, a membrane, a desalting step, an affinity column and the like.

22) An appparatus according to claim 21, wherein said sample microstructure, preferably comprising a network of interconnected microstructures, is used to

collect fractions from said separation means and further dispense them or part of them into the mass spectrometer by electrospray generation.

23) An apparatus according to any preceding claim, which is supported in a device for the precise positioning of the microstructure outlet in front of the MS entrance and/or the facilitation of the electrical connection(s) with one or a plurality of power supplies and/or the introduction of the sample and/or sheath liquid solution(s) with minimized dead volume.

24) An apparatus according to any preceding claim, wherein a third microstructure is used to introduce a sheath gas in the spray.

25) A method of dispensing a sample for subsequent analysis by electrospray mass spectrometry using the apparatus of any one of claims 1 to 24, comprising the steps of applying a voltage to the sheath liquid solution in order to initiate the spray and of imposing another voltage to the sample solution in order to induce a flow of sample, both sheath liquid and sample solutions being mixed directly in the Taylor cone.

26) A method according to claim 25, wherein the proportion of sheath liquid and of sample solutions sprayed is controlled by the difference of the voltage applied in the sheath liquid and that applied in the sample solution.

27) A method according to claim 25 or 26, wherein a floating voltage is applied between the sample solution and the sheath liquid.

28) A method according to claim 27, wherein an aqueous sample solution is sprayed

29) A method according to any one of claims 25 to 28, comprising introducing a compound of known concentration in either or both of the sample and/or the sheath liquid solutions (internal standard(s)).

30) A method according to claim 29, comprising the step of controlling the proportion of sheath liquid and sample solution sprayed and/or of performing quantitative mass spectrometry analyses.

31) A method according to any one of claims 25 to 30, comprising immobilizing molecules of the sample reversibly on a solid support, and releasing said molecules from the solid support into the sample microstructure by a spraying buffer or by a gradient of different solvents.

32) A method according to any one of claims 25 to 31, comprising the step of filling said sample microstructure, or immobilizing or covalently binding to the surface of said microstructure or to a solid support (such as a membrane, a gel, a sol-gel, beads or the like), a biological or a chemical compound, such as e.g. proteins, enzymes, antibodies, antigenes, sugars, oligonucleotides, DNA, cells or an organic compound, in said sample microchannel or to a solid support (as a membrane, a gel, a sol-gel, beads or the like), so as to perform a biological assay such as enzymatic, affinity, activity, immunological and/or cellular assays and/or to perform a chemical assay such as solubility, permeability or lipophilicity tests and/or to perform enzymatic or chemical digestion, sample derivatization or electrochemically induced reactions such as protonation, tagging using quinones or any other redox reactions, with subsequent analysis by electrospray mass spectrometry.

33) A method according to claim 32, wherein at least one affinity agent is immobilized on said solid support, said affinity agent being selected from antibodies, antigens, oligonucleotides, DNA strains and the like.

34) A method according to claim 32 and 33, wherein after the step of immobilizing the molecules of the sample, the solid support is placed in contact with the sample microstructure.

35) A method according to claims 32 to 33, wherein a chemical reaction and/or an affinity reaction occurs in or on said solid support prior to the releasing step.

36) A method according to claim 35, wherein said chemical reaction and/or affinity reaction comprises at least one of desalting, enzyme or chemical digestion, chemical transformation and purification.

37) A method according to any one of claims 32 to 36, wherein said solid support is selected from polymers, ceramics, metallic and glass materials; e.g. polyvinylidenefluoride (PVDF), nitrocellulose, cellulose acetate, acrylamide, agarose, or the like.

38) A method according to claim 32, wherein after the step of coating a compound in the sample microstructure, a buffer is introduced to partially or totally dissolve said compound for subsequent analysis by electrospray mass spectrometry.

39) A method according to any one of claims 32 to 38, wherein a separation is performed in the sample microstructure and/or an partial or total extraction in a solution in contact with the sample solution is performed prior to spraying of the sample solution.

40) A method according to any one of claims 32 to 39, wherein an organic phase is deposited at the inlet of the sample microstructure in order to avoid evaporation of the sample solution to be sprayed.

41) A method according to any one of claims 32 to 40, wherein the sample and sheath liquid solutions are applied directly in the inlet reservoirs of the respective microstructures and sprayed into the MS, even without application of an external force (e.g. back pressure).

42) A method of fabricating an apparatus for dispensing a sample for subsequent analysis by mass spectrometry, comprising the steps of taking a substrate of electrically insulating material, fabricating at least two covered microstructures, both having an outlet at the edge of the substrate where the spray is to be generated by application of a voltage and an inlet for fluid introduction, so

that the sample and sheath liquid solutions to be sprayed from the microstructures through these outlets are mixed in the Taylor cone.

43) A method of fabricating an apparatus according to claim 42, comprising the step of taking a substrate which is a multilayer body, fabricating at least one covered microstructures in a plurality of layers, assembling said plurality of layers and optionally cutting the assembled multilayer body, so as to obtain at least two covered microstructures, both having an outlet at the edge of the substrate where the spray is to be generated by application of a voltage and an inlet for fluid introduction, so that the sample and sheath liquid solutions to be sprayed from the microstructures through these outlets are mixed in the Taylor cone.

44) A method according to claim 42 or 43, comprising the step of integrating electrically or ionically conductive means for applying a voltage to the sample and/or sheath liquid solution(s), said conductive means having a controlled size and location.

45) A method according to any one of claims 42 to 44, wherein said conductive portion means is formed by laser photoablation, by plasma etching, by chemical etching, by deposition of an ink, of a conductive polymer, by integration of an ion exchange material, by metal deposition, by sputtering or the like.

46) A method according to any one of claims 42 to 45, wherein said conductive means is integrated in the cover of the microstructures.

47) A method according to any one of claims 42 to 46, comprising adding an electrode in a reservoir connected to the inlet of at least one of the covered microstructures, such as to apply a voltage from outside the microstructure(s).

48) A method according to any one of claims 42 or 47, wherein the substrate is a polymer material.

49) A method according to any one of claims 42 or 48, wherein the microstructures are formed by by laser photoablation, UV-Liga, embossing,

injection molding, solvent casting, light or thermal induced polymerization, silicon technology or superposition of layers at least one comprising mechanically drilled grooves, hollows or holes.

50) A method according to any one of claims 42 or 49, wherein a plurality of apparatuses are fabricated in the same substrate, thereby creating an array of apparatuses.

51) A coupling device comprising one or a plurality of apparatus(es) according to any one of claims 1 to 24, further comprising one or a plurality fluid connection(s) for minimizing dead volumes at the microstructure inlets, and/or electrical connection(s) for application of potential differences in the microstructures and/or a system enabling the precise positioning of the apparatus(es) in front of the MS entrance.

52) An analytical instrument comprising an array of apparatuses, each according to any one of claims 1 to 24.

53) A method of analyzing a plurality of samples, comprising taking an array of apparatuses, each according to claim 1 to 24, using a plurality of the apparatuses in turn to collect a sample, and dispensing each sample from the respective apparatus, and analyzing each sample by mass spectrometry.

54) A method according to claim 53, wherein said samples are collected from an analytical system, e.g. a chromatograph, an electrophoretic unit, a separation unit or an affinity system.

55) A method of performing chemical or biological assay using one apparatus or an array of apparatus, each according to claims 1 to 24, with detection by electrospray mass spectrometry.

56) A method according to claim 55 wherein said chemical or biological assays are selected from enzymatic, affinity, activity, immunological and/or cellular assays, solubility, permeability or lipophilicity tests.

Abstract

Apparatus for Dispensing a Sample in Electrospray Mass Spectrometers

The present invention relates to an apparatus to dispense a sample for subsequent electrospray ionisation (ESI) mass spectrometry (MS) analysis, to a method of fabricating such apparatus and to applications of such apparatus in biological and chemical analysis. The apparatus consists of an electrically non-conductive substrate comprising at least two covered microstructures (generally microchannels) having one extremity formed at the edge of the substrate, one of said microstructures containing the sample to be dispensed into a mass spectrometer by electrospray ionization and at least a second of said microstructure containing a solution used as sheath liquid, said at least two microstructures being formed in such a manner that the sample and the sheath liquid solutions are mixed directly in the Taylor cone of the spray. This apparatus enables the control of the flow-rates in the various microstructures, and to spray purely aqueous sample solutions, as well as to perform derivatization of the sample solution, reaction between species. Integration of an internal reference in either or both the sample and the sheath liquid solution also allows to control the sampling and to perform quantitative mass spectrometry analysis. This apparatus may be used as simple coupling means for electrospray mass spectrometers, but it may also be connected to other separation systems like an chromatography unit or an electrophoress apparatus arious, and it may also be used for performing various assays like e.g. immunological tests, enzymatic reaction, DNA tests, affinity reactions, desalting step, permeability measurements, lipophilicity or solubility assays that can even be carried out within the sample microstructure and hence on-line with mass spectrometry detection. Various other applications of this apparatus are also disclosed in the present application.

Fig. 1

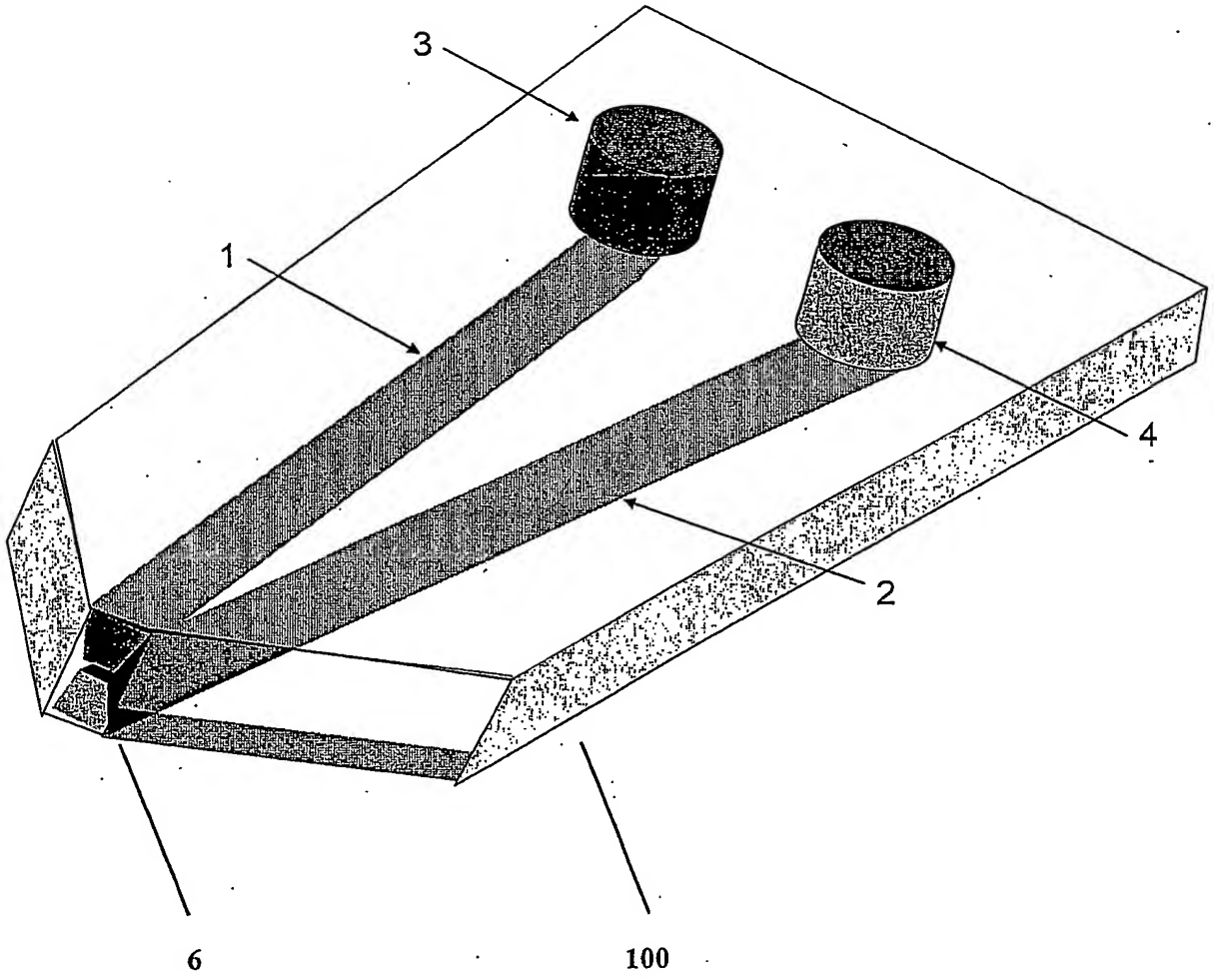


Fig. 2

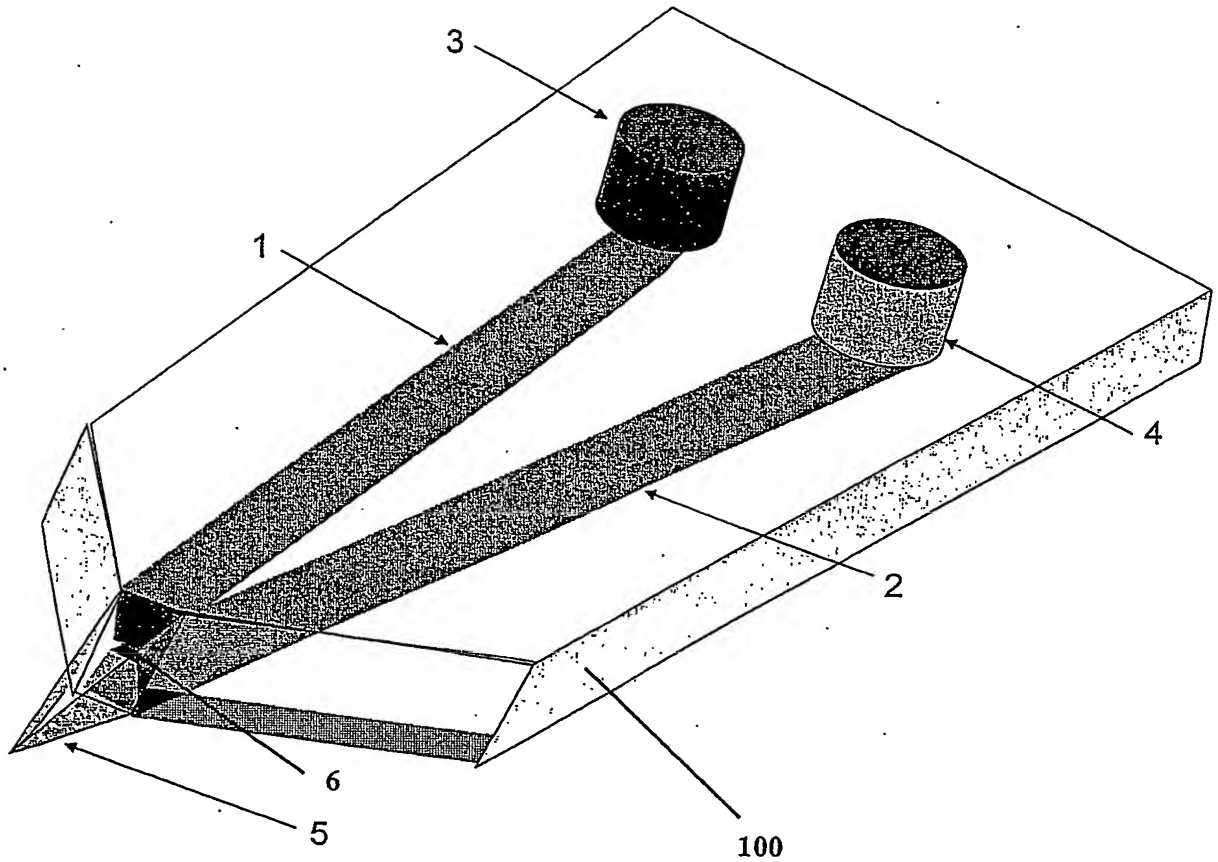
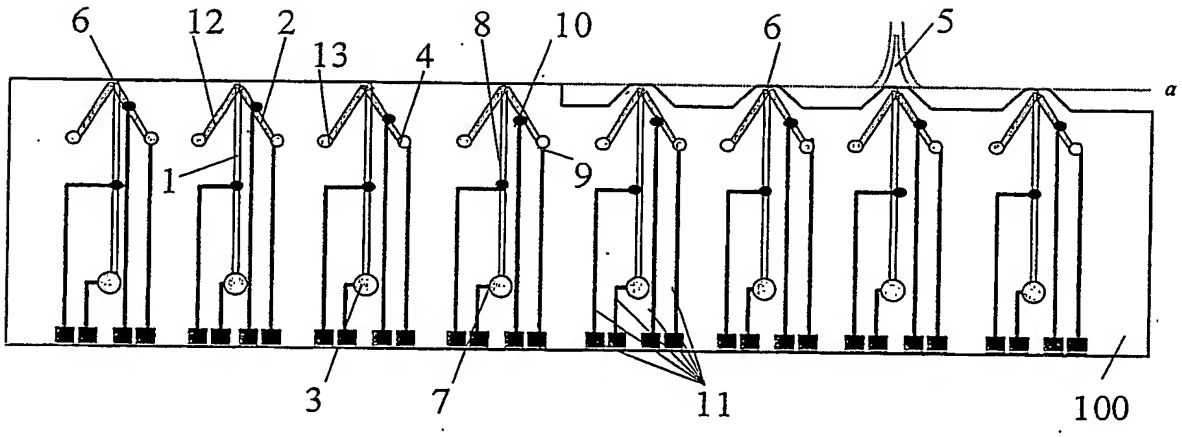


Fig. 3

A)



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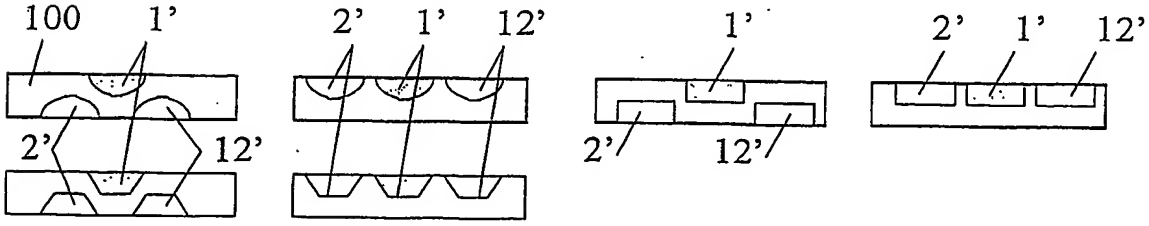


Fig. 4

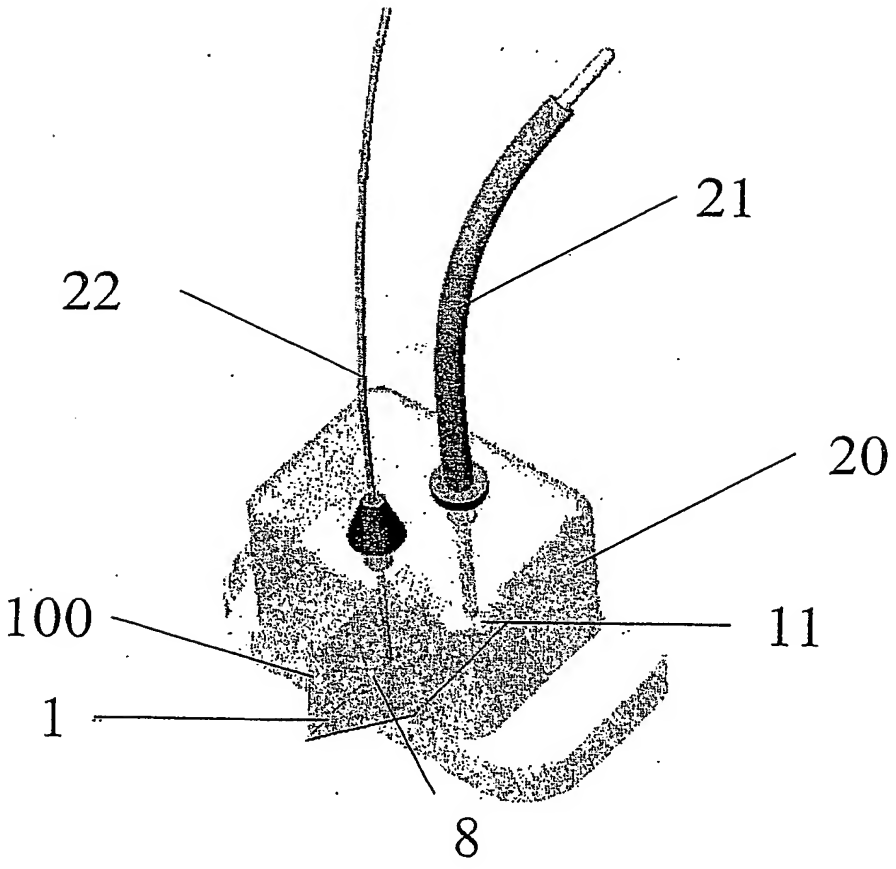
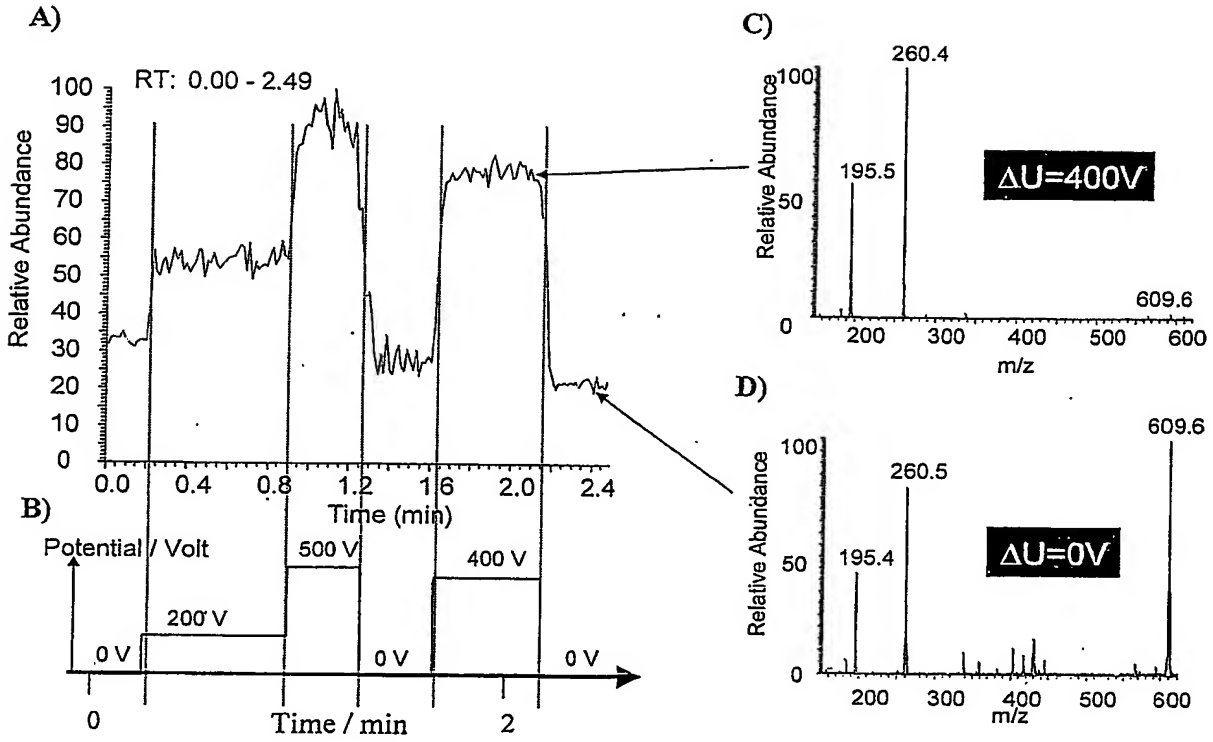


Fig. 5


A)
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Relative Abundance
Time (min)
B)
Potential / Volt
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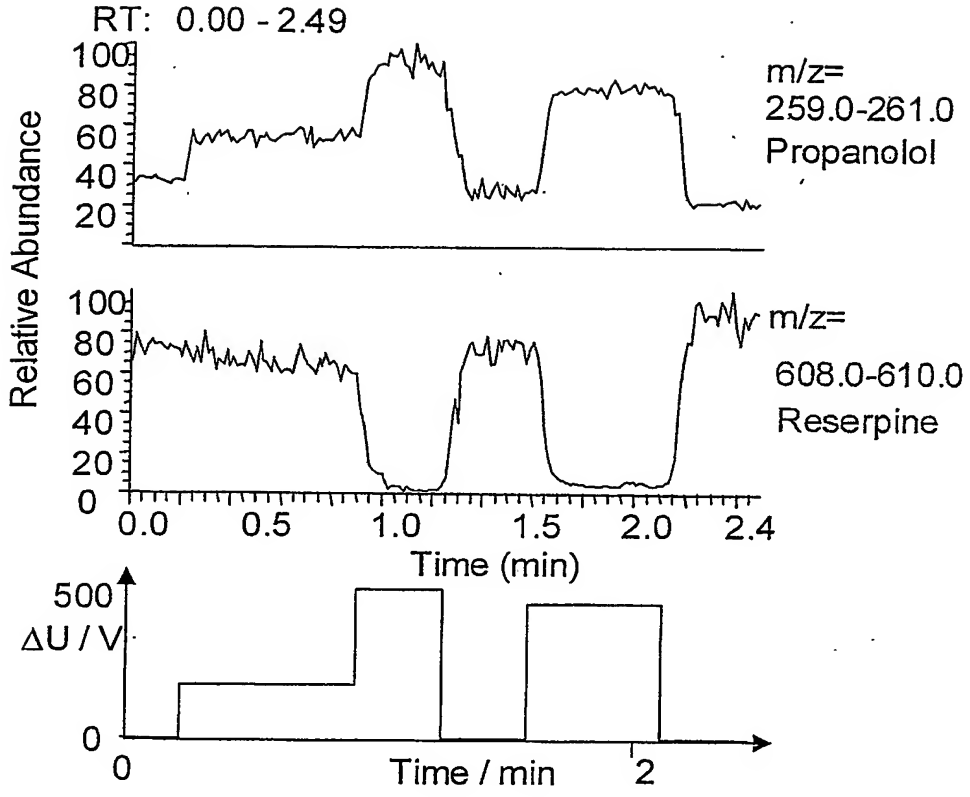
500 V
400 V
0 V
0 V
0 V
0
Time / min
2
C)
260.4
195.5
ΔU=400V
609.6
m/z
D)
609.6
260.5
195.4
ΔU=0V
m/z

Fig. 6A


RT: 0.00 - 2.49
Relative Abundance
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60
40
20
m/z=
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Propanolol
100
80
60
40
20
0
m/z=
608.0-610.0
Reserpine
0.0
0.5
1.0
1.5
2.0
2.4
Time (min)
500
ΔU / V
0
0
Time / min
2

Fig. 6B

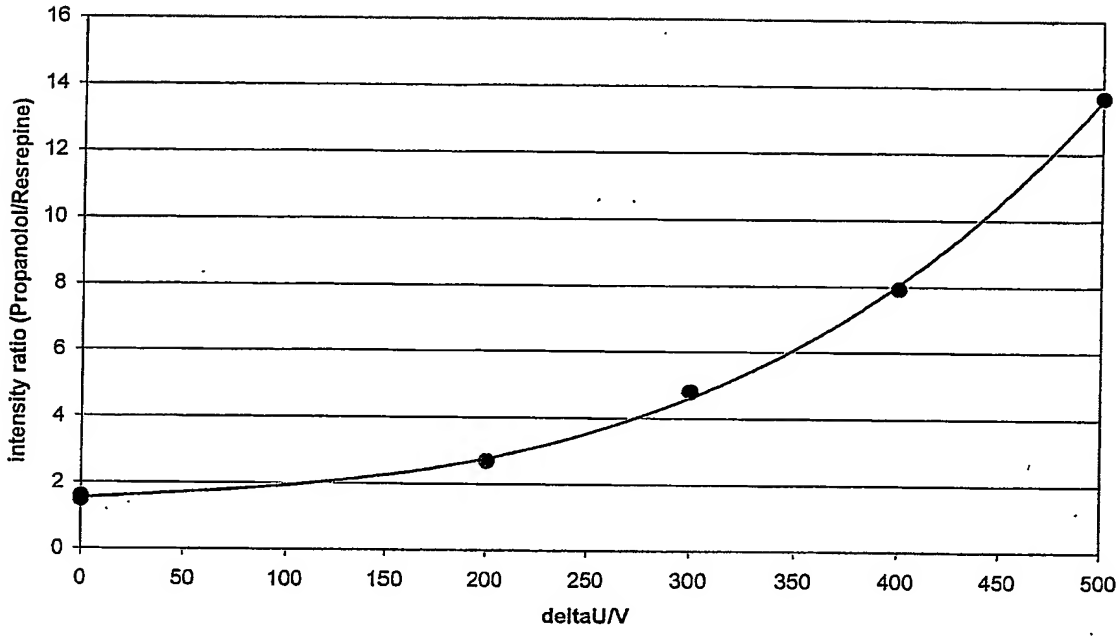
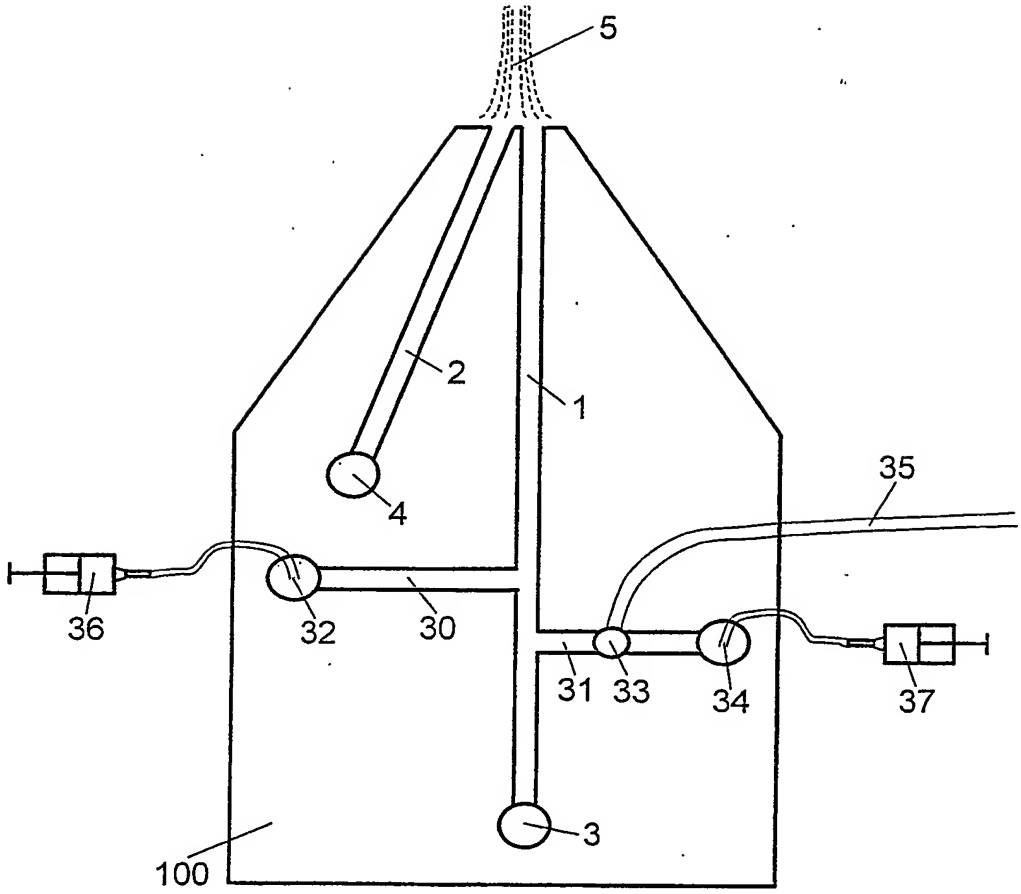

intensity ratio (Propanolol/Resrepine)
16
14
12
10
8
6
4
2
0
0
50
100
150
200
250
300
350
400
450
500
deltaU/V

Fig. 7



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